Atlantic Water flow to the Kara Sea: Comparing model results with observations[#]

M.J. Karcher[1*], M. Kulakov[2], S. Pivovarov[2], U. Schauer[1], F. Kauker[1], R. Schlitzer[1]

[1]Alfred Wegener Institute for Polar and Marine Research, Columbusstrasse 2, 27568 Bremerhaven, Germany
[2]Arctic and Antarctic Research Institute (AARI), St. Petersburg, Russia

Abstract

The Kara Sea, due to its geographic location downstream of the main eastward Atlantic Water inflow through the Barents Sea, is strongly influenced by the history of the Atlantic Water masses which enter at its western entrances: the Kara Strait and the passage between Franz Josef Land and Novaya Semlya. Little is known about the interannual variability of temperature, salinity and volume fluxes through these entrances.

The present investigation analyzes model results from 1979 to 1999 and compares them to hydrographic observations in the Barents and Kara seas with respect to the interannual variability of Atlantic Water flow through the western entrances of the Kara Sea. Model results and observations suggest the propagation of sequences of warm and cold anomalies through the area of investigation. Most prominent are anomalously cold years 1986, 1993 and 1998 for the Kara Strait throughflow which are associated with weak eastward or even westward flow over periods up to several months. For the passage between Franz Josef Land and Novaya Semlya, the entire period of the 1990s is characterized by warm deep water temperatures. In the early and late 1990s also the eastward volume fluxes are at their maximum. We discuss an Empirical Orthogonal Function analysis of the velocity in the Barents and Kara Seas. The warm and cold phases are associated with the first two modes of the velocity pattern in the domain. The links of these velocity patterns with the large scale sea level pressure are discussed.

1 Introduction

Apart from a large input of freshwater by the rivers, the hydrography of the Kara Sea is strongly influenced by lateral fluxes of Atlantic derived watermasses (Pavlov and Pfirman, 1995). These enter through three entrances: from the Barents Sea through the Kara Strait and via the passage between Franz Josef Land and Novaya Semlya. A third inflow occurs through St. Anna Trough from the North (Fig. 1). The source of the first two of theses Atlantic Water inflows is the water which intrudes the Barents Sea from the Norwegian Sea through the 'Barents Sea Opening (BSO)', the gap between Spitsbergen and the North Cape of Norway. The water consists of a mixture of Atlantic Water from the Norwegian Atlantic Current and fresher water of the Norwegian Coastal Current. The branches entering through each of the entrances have experienced very different ambient conditions during the passage through the Barents Sea.

[#] In: Proceedings in Marine Science, *Siberian River Run-off in the Kara Sea: Characterisation Quantification, Variability and Environmental Significance*, R.Stein, K. Fahl, D. K. Fütterer, E. Galimov (Eds.), 2003

[*] corresponding author: mkarcher@awi-bremerhaven.de

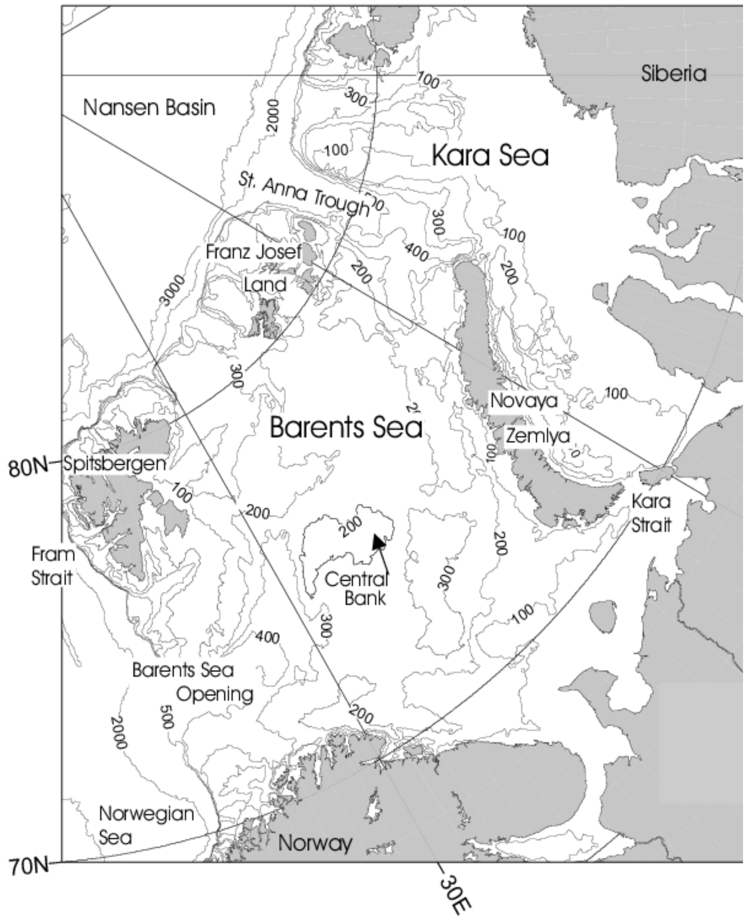


Fig. 1: Topography of the Barents and Kara Sea with names used in the text.

The coastal branch passing Kara Strait has its largest influence on the hydrographic conditions in the southern and eastern Kara Sea (Pavlov and Pfirman, 1995; Harms and Karcher, 1999). The branch entering through the passage between Franz Josef Land and Novaya Semlya, on the other hand, influences the northern part of the Kara Sea. Due to heat loss, and potential subsequent ice formation with brine release, part of this water increases in density and continues towards St.Anna Trough steered by the local topography. It enters the deep basin of the Arctic Ocean on the eastern slope of the trough at mid-depths. It is unclear so far, whether part of the flow through the passage between Franz Josef Land and Novaya Semlya recirculates southward at the northern tip of Novaya Semlya and excerpts a significant influence on the hydrography of the Kara Sea south of 76°N (Pavlov and Pfirman, 1995; Loeng and Sætre, 2001).

On the western slope of St.Anna Trough the third branch of Atlantic derived watermasses enters the Kara Sea. It stems from the Fram Strait branch of Atlantic Water which spreads from Fram Strait eastward along the Barents Sea slope. Due to the capping of this water by fresh water and ice it retains a comparably high temperature. Part of it recirculates south and westwards after passing Franz Josef Land. Its traces are clearly visible as a high temperature core in hydrographic sections between Franz Josef Land and Novaya Semlya (Schauer et al., 2002).

For all branches of Atlantic-derived water which enter the Kara Sea, a large seasonal and interannual variability can be expected, which has hardly been discussed in the literature. It is the aim of the present investigation to describe the variability of these inflows as they result from a numerical experiment with a coupled ice-ocean model and from observations. The source of the observations is the 'BarKode' database (Golubev and Zuyev, 1999).

The present study is conducted within the context of the German-Russian project SIRRO (Siberian River Run-Off) in the course of which two coupled ice-ocean models are used. Harms et al. (this volume) describe a high resolution model of the southeastern Kara Sea aiming at the regional processes in the southern Kara Sea. Here we present results from the large-scale model effort concentrating on the oceanic conditions imposed on the Kara Sea by the three sources of inflowing Atlantic water.

2 Data sources: Model and Observations

2.1 The model

The present investigation makes use of a version of the ocean model MOM-2 (Pacanowski, 1995) which has been adapted to the Arctic and subarctic regions at the Alfred Wegener Institute for Polar and Marine Research (Karcher et al., 2003; Kauker et al., 2003). The model domain extends from the northern North Atlantic into the Nordic Seas and the Arctic Ocean. At the southern model boundary near 50°N an open boundary condition has been implemented allowing the outflow of tracers and the radiation of waves. At inflow points determined by the model, temperature and salinity are specified according to climatology (Levitus et al., 1994). Barotropic velocities normal to the boundary are specified from a lower resolution version of the model that covers the entire North Atlantic (Köberle and Gerdes, 2003). The horizontal resolution is 0.25° x 0.25° on a rotated spherical grid which is introduced to avoid numerical difficulties at the Pole.

In the vertical, the model has 30 unevenly spaced levels, the five top levels have a constant thickness of 20 m. Due to numerical constraints, the minimum number of levels in the water column is three, which gives a minimum depth of 60 m. Areas with a bottom depth less than 10 m are treated as land. Areas with depths between 10 and 60 m are deepened to the minimum depth. Bottom topography is based on the Etopo5 data set of the National Geophysical Data Center. Modifications were made to open two channels in the Canadian Archipelago connecting the Arctic Ocean with Baffin Bay.

The ocean model is coupled with a dynamic-thermodynamic sea ice model (Hibler, 1979; Harder, 1998) which employs a viscous-plastic rheology. The thermodynamics is formulated following Semtner (1976). Freezing and melting are calculated by solving the energy budget equation for a single ice layer with optional snow cover.

The freezing point of sea water is salinity dependent. Sea ice and ocean models use the same time step and the same horizontal grid, the calculation of non-linear ice-ocean momentum fluxes is based on ocean currents which are temporally smoothed using moving 4-daily means. Outflow of ice out of the domain is allowed at the southern boundary and at Bering Strait. The models are coupled following the procedure devised by Hibler and Bryan (1987). The surface heat flux is calculated from standard bulk formulae using prescribed atmospheric data and sea surface temperature predicted by the ocean model.

Initial conditions for potential temperature and salinity were taken from the Arctic Ocean EWG-climatology for winter (NSIDC, 1997). Where the model domain exceeds the EWG-climatology domain, the climatology of Levitus et al. (1994) has been used. The model is forced with daily mean 2-meter air temperature and dew point temperature, cloudiness, precipitation, wind speed and surface wind stress. For the first 20 years of spin-up, a climatology of these atmospheric data is used, which consists of a climatological mean seasonal cycle of the period 1979-1993 to which a typical daily variability was added (OMIP-climatology) (Röske, 2001). After the spin-up the forcing consists of daily mean atmospheric data from the ECMWF reanalysis for the period 1979 - 1993 (Gibson et al., 1997). For the period 1994 -1999 2-meter air temperature and dew point temperature, wind speed and surface wind stress are taken from the ECMWF analysis. Cloudiness and precipitation data for this period are taken from the OMIP-climatology. Freshwater influx from rivers is not explicitly included. To account for river run-off and diffuse run-off from the land, as well as to include the effect of flow into the Arctic through Bering Strait on the salinity, a restoring flux (with an adjustment time scale of 180 days) is added to the surface freshwater flux. The restoring flux is calculated in reference to observed data from the EWG-atlas (NSIDC, 1997) for the Arctic Ocean and the Nordic Seas and Levitus et al. (1994) for the rest of the domain. The effect of the restoring flux on the surface salinity for this and other Arctic Ocean models is documented in Steele et al. (2001).

The entire hindcast integration covers a period of 21 years (1979-1999) after spin-up.

2.2 Observations

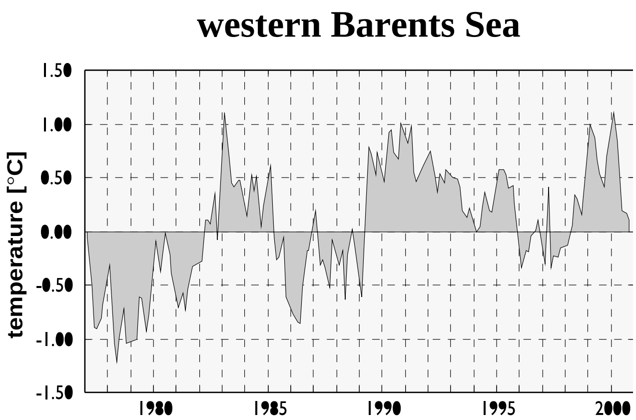
For a comparison with the model derived data we are able to make use of two sources of observational data. The bulk of data used here stems from the dataset 'BarKode' which compiles numerous observations in the Barents and Kara Seas from the time period 1898 to 1998 (Golubev and Zuyev, 1999). For this dataset the original data had been checked for errors and interpolated to standard depth horizons.

The second source are data from the archive of the Arctic and Antarctic Research Institute in St.Petersburg, Russia, covering single years between 1979 and 1995. The location of these data is limited to the section between Franz Josef Land and Novaya Semlya and the Kara Strait. Both available datasets have been converted into the format 'Ocean Data View (ODV)' (www.awi-bremerhaven.de/GEO/ODV/index.html). From the combined dataset we will extract subsets of data for the summer on horizontal and vertical sections.

3 Results

3.1 The large-scale situation 1979 - 1999

In a recent modeling study based on the same numerical experiment analyzed here, Karcher et al. (2003) describe the large scale situation in the Arctic Ocean during the period 1979-1999 with respect to the interannual variability of the horizontal temperature transport. In accordance with observations from the Nordic Seas and the deep basins of the Arctic Ocean, Karcher et al. (2003) describe the advection of Atlantic Water temperature anomalies with the two prevailing flow branches. The first branch enters with the West Spitsbergen Current through Fram Strait and moves along the continental slope of the Barents Sea below the halocline eastwards into the Eurasian Basin. The second branch enters from the Nordic Seas into the Barents Sea and continues via the passage between Franz Josef Land and Novaya Semlya into the central Arctic Ocean. In the 1980s two cold anomalies and a warm one entered the Arctic Ocean with the two branches, exhibiting an interannual variability of about 0.5-1.0°C (Fig. 2). A larger and longer lasting positive temperature anomaly entered in the first half of the 1990s. This anomaly of the 1990s is responsible for the bulk part of the warming of the Atlantic Water layer of the Arctic Ocean observed in the 1990s (Quadfasel et al., 1991; Carmack et al., 1995). The analysis of Karcher et al. (2003) shows that three quarters of the additional heat in the 1990s entered the Arctic Ocean basins with the Fram Strait branch. About one quarter of the heat



[H. Loeng, IMR Bergen, pers. comm]

Fig. 2: Observed timeseries of Atlantic Water temperature from the western Barents Sea (courtesy of H. Loeng, IMR Bergen).

surplus can be traced back to the Barents Sea branch, despite the enormous heat loss of the ocean to the atmosphere that takes place west of Novaya Semlya.

3.2 Atlantic Water inflow into the Kara Sea from modeling results

Figure 3 visualizes the mean flow and mean potential temperature at 100 m depth in the area of investigation as derived from the period 1979 to 1999 of the model experiment. The flow of Atlantic Water in the Barents Sea follows several meandering paths which are guided by topography. At about 30°E the incoming flow from the west separates into two branches. One branch turns north- and subsequently east towards Franz Josef Land before it sharply turns southward to the northern tip of Novaya Semlya. Here it joins with the second branch which had continued further eastward and followed the west coast of Novaya Semlya. The rejoined flow enters Kara Sea through the southern part of the Franz Josef Land to Novaya Semlya passage. We will call the first of the two branches the 'central branch' of Atlantic Water in the Barents Sea, while the latter will be called the 'southern branch'. The near coastal part of the southern branch which twists off in the Pechora area and flows into the Kara Sea through the Kara Strait, is not visible in Figure 3 since it is confined to the upper 60 m of the water column.

In the following section we will present the model results with respect to the flow into the Kara Sea via these two gaps: the Kara Strait and the passage between Franz Josef Land and Novaya Semlya. We will present timeseries of monthly and yearly means for temperatures, temperature and volume fluxes at the openings of the Kara Sea. The temperature fluxes are calculated based on weekly means of flow velocities and hydrographic parameters. The reference temperature is -0.86°C, which is the mean temperature of the Kara Sea during the 21 years of simulation.

<u>The southern source: Kara Strait</u>

The development of the water temperature at the Kara Strait during the 21 years of simulation shows a large seasonal cycle with up to 2°C amplitude, a maximum in late summer, and a large interannual variability of the annual maximum (Fig. 4). The difference between the coldest (1998) and warmest summer (1989) during the 21 years is 3.5°C. The years 1985-1987, 1993 and 1998 are characterized by cold summers. Naturally, the variability of the late winter minimum is much smaller, with about 0.5°C difference between the cold winter of 1990 and the relatively warm one in 1991.

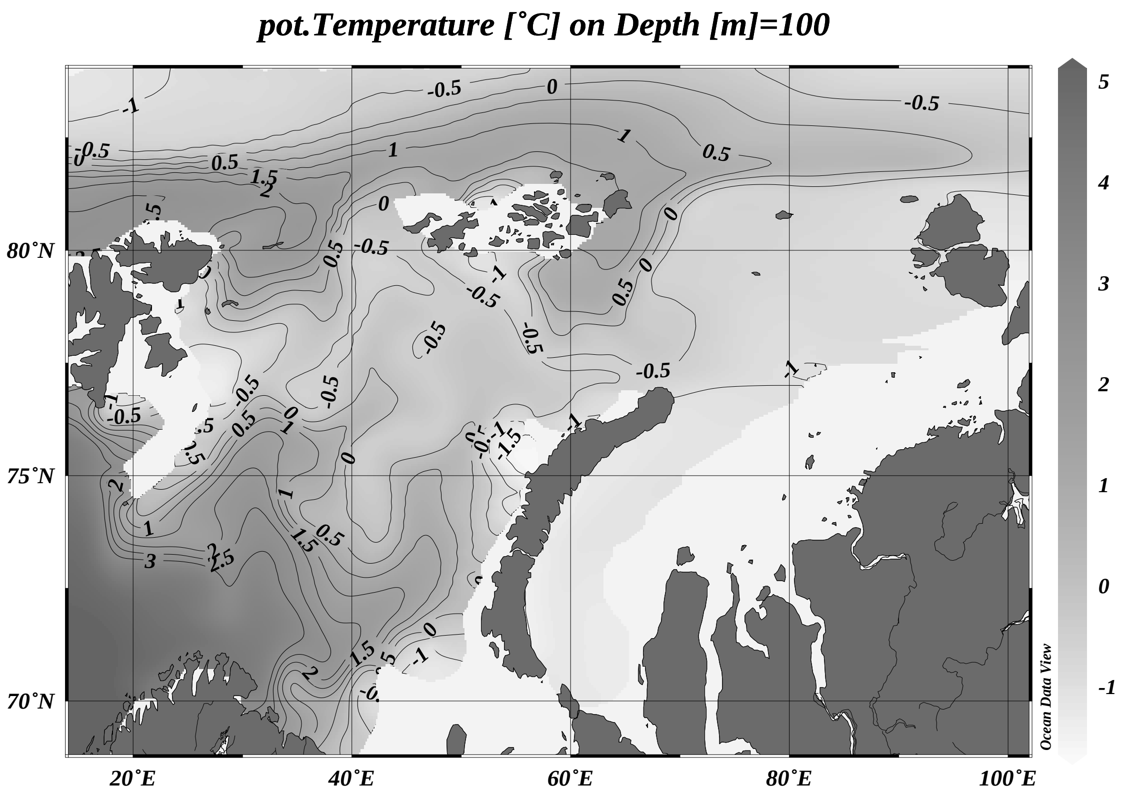


Fig. 3a: Mean potential temperature at 100 m depth for the period 1979 to 1999. The figure shows a subdomain of the entire model domain covering the Barents and Kara Seas.

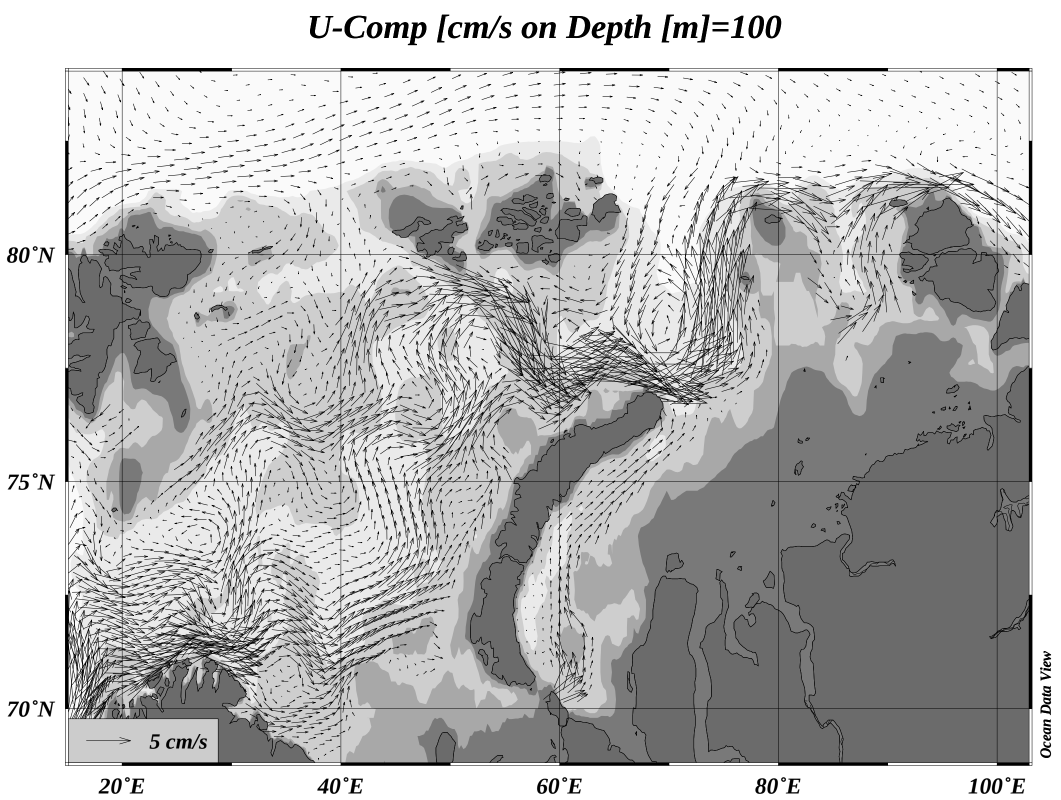


Fig. 3b: Mean potential velocity at 100m depth for the period 1979 to 1999. The figure shows a subdomain of the entire model domain covering the Barents and Kara Seas.

The volume flow through Kara Strait is dominantly eastward, typically between 0.2 and 0.6 Sv on a yearly mean basis. Monthly means may be as large as 1.4 Sv net eastward (Fig. 5a). These values are in the range of throughflow discussed in literature. Loeng et al. (1997) indicate a range from 0.05 to 0.7 Sv from geostrophic calculations and current meter moorings. The seasonal cycle differs in shape and amplitude from year to year. It usually has a large amplitude O(0.5 Sv) and features the strongest eastward throughflow for the winter months, while the weakest and sometimes reversed net flows occur in the

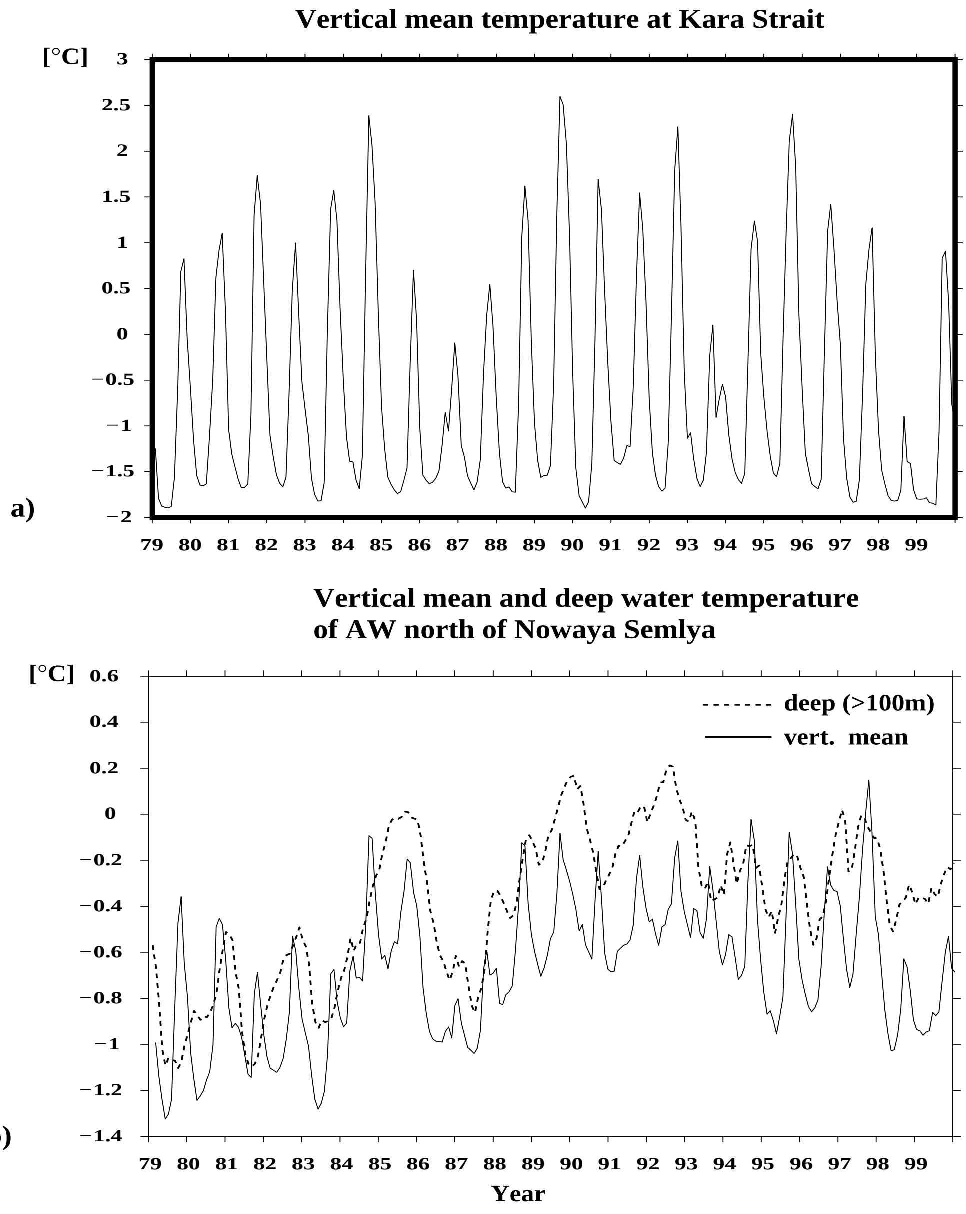
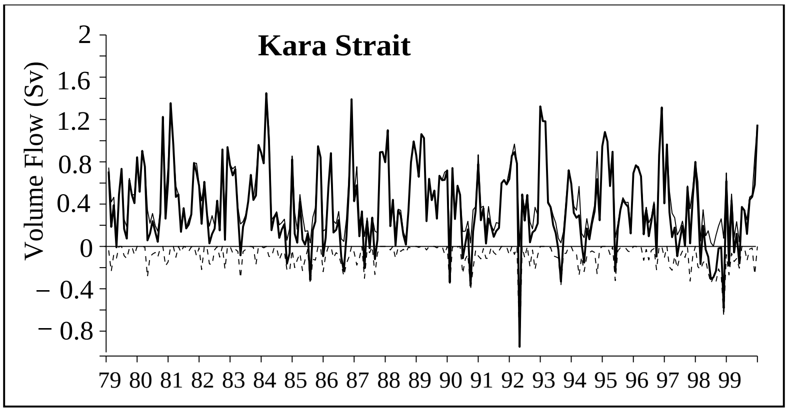


Fig. 4: Timeseries of vertical mean monthly mean potential temperatures from the model simulation at a) the Kara Strait (total water column) and b) the southern part of the passage between Franz Josef Land and Novaya Semlya which captures the eastward flowing water of Atlantic origin. The stipled line represents the vertically averaged temperatures below 100 m, the thin line stands for the total water column.

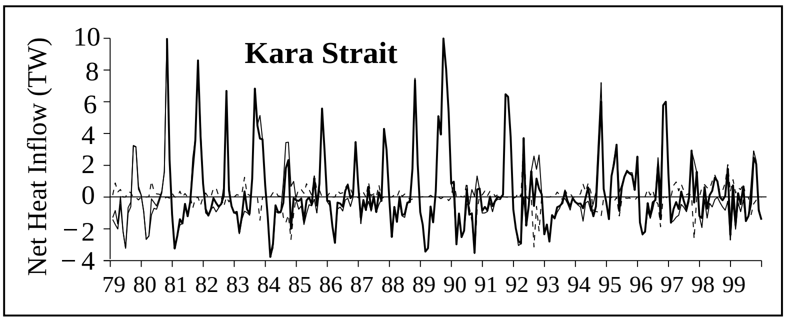
summer months. Most unusual periods are from late 1988 to mid 1990 with an intense, long-lasting eastward flow, spring 1992 with a net westward flow of almost 1 Sv, and 1998, when a sluggish eastward flow and strong westward flow add up to net westward monthly mean flows of 0.1 to 0.6 Sv over three quarters of a year. This period coincides with the coldest phase of the vertically integrated temperatures in the strait (Fig. 4a). For the temperature fluxes (Fig. 5b) we find slightly reduced seasonal amplitudes in the 1990s as compared to the previous decade. The year 1998 again shows exceptional behavior with a large outflow of cold water from the Kara Sea.

The northwestern source: FJL-Novaya Semlya

The most prominent signal of the long-term temperature development of the Barents Sea Water at the Franz Josef Land to Novaya Semlya passage is a regime shift from cold to warm of about 0.8°C from the 1980s to the 1990s (Fig. 4b). Superimposed on this shift is a seasonal signal in the overall vertical mean, which is irregular in terms of phase as well as in terms of amplitude. The deep water temperature on the other hand has only a smooth interannual signal superimposed on the shift. A first warm anomaly occurs in the mid 1980s. This anomaly and a second one in the early nineties has recently been identified by Karcher et al. (2003) as features stemming from the Nordic Seas (compare also Fig. 2). Both signals - in the water below 100m - are obviously able to survive the intense heat loss along the path of the BSO inflow water across the Barents Sea shelf. Interestingly the drop in temperature at the BSO after 1995 to values like before 1989 does not appear at the Franz Josef Land to Novaya Semlya passage. Especially the late summer temperature maxima of the vertical mean temperature stay on a high level throughout most of the 1990s. The two coldest summers of 1987 and 1998 coincide with the coldest summers found in the Kara Strait temperatures (Fig. 4a).



a)



b)

Fig. 5: Timeseries of vertically integrated a) volume flux and b) temperature flux through Kara Strait. The thin lines represent eastward and westward (stipled) flux, the thick lines are the net flux, the direction is positive eastward.

The inflow of volume from the Barents Sea via the Franz Josef Land to Novaya Semlya passage (Fig. 6a) is characterized by a maximum in the mid 1980s and in the early and late 1990s. This sequence mirrors the volume fluxes at the BSO (Karcher et al., 2003). The mean eastward volume flux amounts to about 2.5 Sv which reduces to a net eastward flux of about 2.1 Sv when taking into account the westward flux of about 0.4 Sv. These numbers are somewhat larger than the estimates of 1.9 Sv eastward and 0.3 Sv westward (Loeng et al., 1994) or 1.5 Sv eastward and 0.1 Sv westward (Schauer et al. 2003) which were both based on current meter records which covered 65% of the passage from October 1991 to September 1992. The eastward temperature flux through the Franz Josef Land to Novaya Semlya passage (Fig. 6b) reflects the shift in the temperature between 1980s and

a)

b)

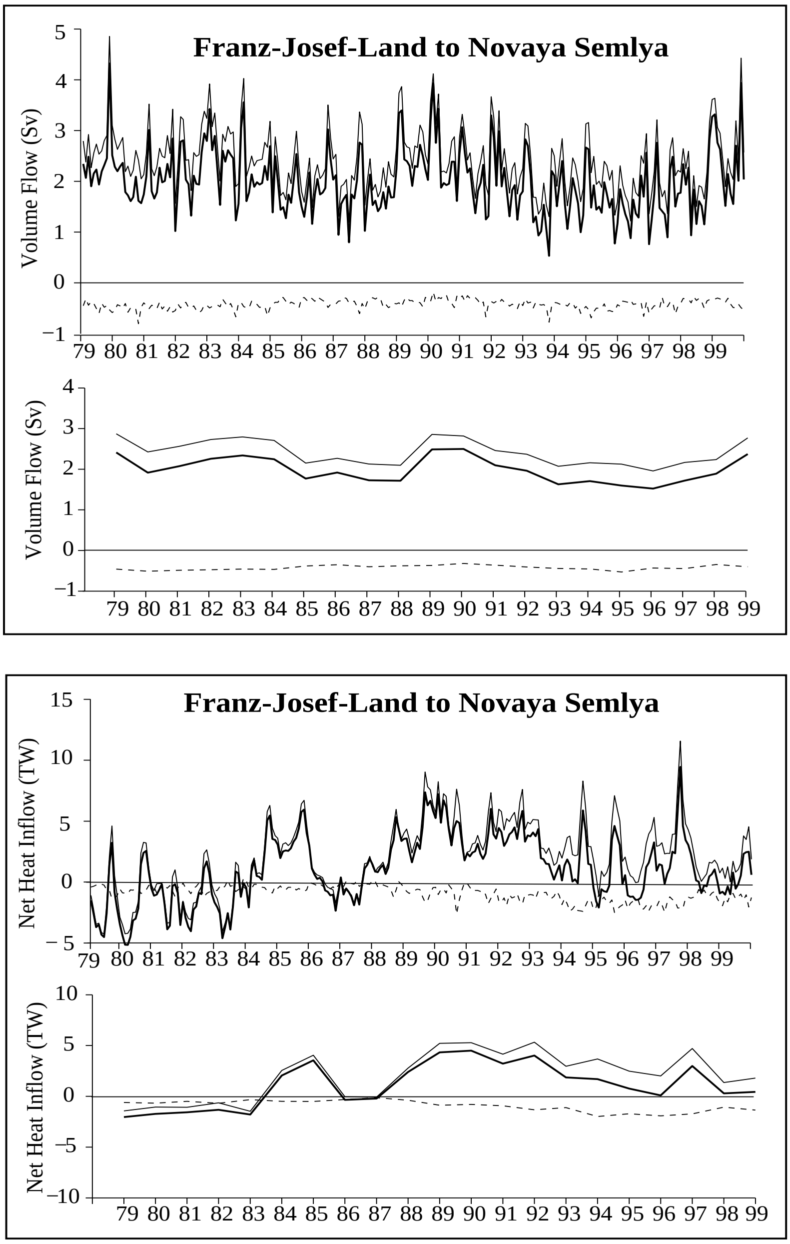


Fig. 6: Timeseries of vertically integrated a) volume flux and b) temperature flux through the passage between Franz Josef Land and Novaya Semlya. The curves in the upper panels are based on monthly means while in the respective lower panels they are based on yearly means. The thin lines represent eastward and westward (stipled) flux, the thick lines are the net flux, the direction is positive eastward.

1990s. Also the water flowing westward carried more heat in the 1990s (stippled line). We can identify the source of this westward moving warm water as a circulation of Atlantic Water from the Fram Strait branch around Franz Josef Land, since a similar increase takes place at the western slope of St.Anna trough (not shown). This will also be evident from temperature and salinity distributions from observations and the model as we will explain in the next section.

3.3 Hydrography from model results and observations

The available hydrographic observations which are located in the area of investigation unfortunately do not allow constructing a complete history of temperature and salinity distributions for the period 1979-1999. However, based on a combination of data from the BarKode dataset and measurements from the hydrographic archive of the AARI we are able to get at least a rough idea on the interannual variability of the hydrography in order to validate the model results. For this purpose, timeseries, vertical and horizontal sections were constructed. For the sake of an easier comparison of observations and model results we used the software ODV for the visualization and interpolation of both. For the construction of the summer maps data from the months June to September have been used for the observations. From the model June to November means are shown.

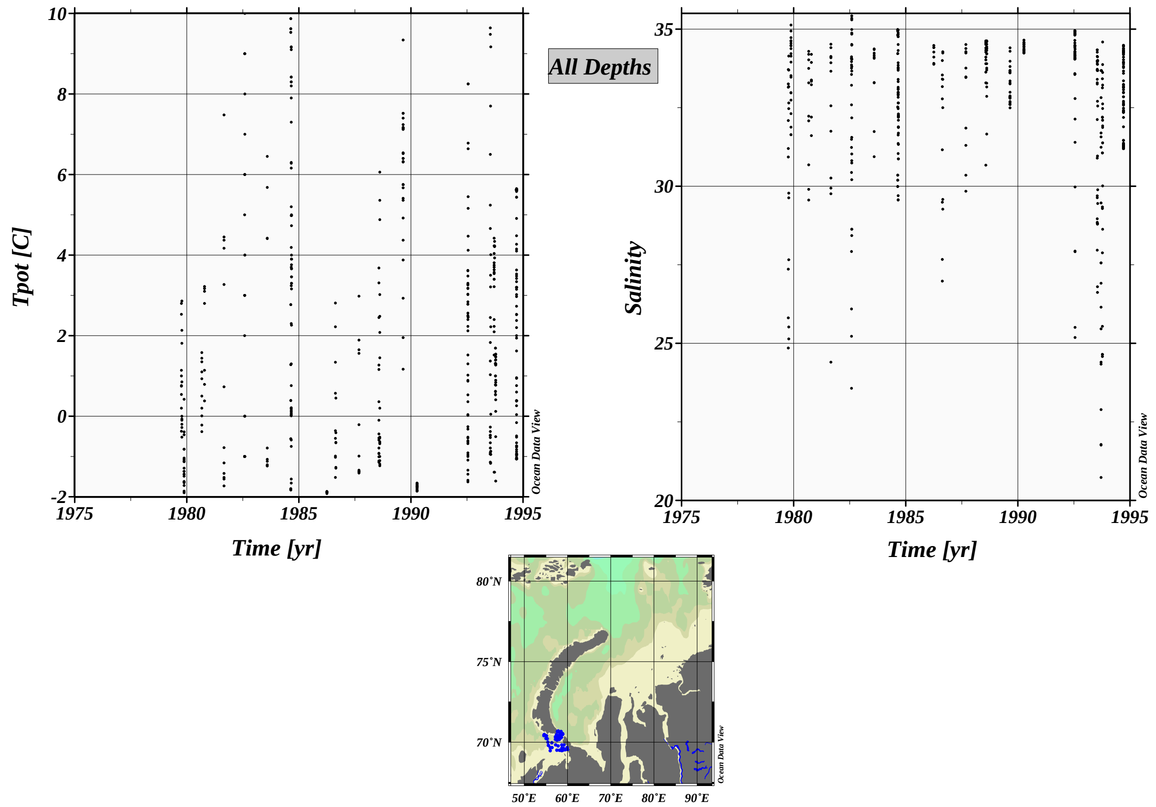


Fig. 7: Observed temperature (upper left) and salinity (upper right) against time at the Kara Strait for all depths. Also shown are a map with the locations of the observations (lower left).

Timeseries from observed hydrography

For the following analysis we use timeseries of observed temperature and salinity at the two source areas discussed in the previous section: Kara Strait and the passage between Franz Josef Land and Novaya Semlya. The observations of temperature in the Kara Strait as displayed in Figures 7 and 8 exhibit similar features on an interannual scale as the modeled timeseries discussed in the previous section. In the Kara Strait (Fig. 7) the maximum temperatures observed in the summer months (July to September) are low in the years 1986 and 1987 while the earlier years of the 1980s and 1989 were warmer. For salinity, several years stand out with extremely low salinity events: 1982, 1986 and 1994, in which minimum salinities are well below 25, where the other years show minimum salinities above 30.

In the deep (> 100m) Barents Sea water at the passage north of Novaya Semlya (Fig. 8) a shift to high temperatures in the 1990s is indicated although the data coverage of the 1990s is sparse. Similar to the model results, a maximum is apparent also in 1985.

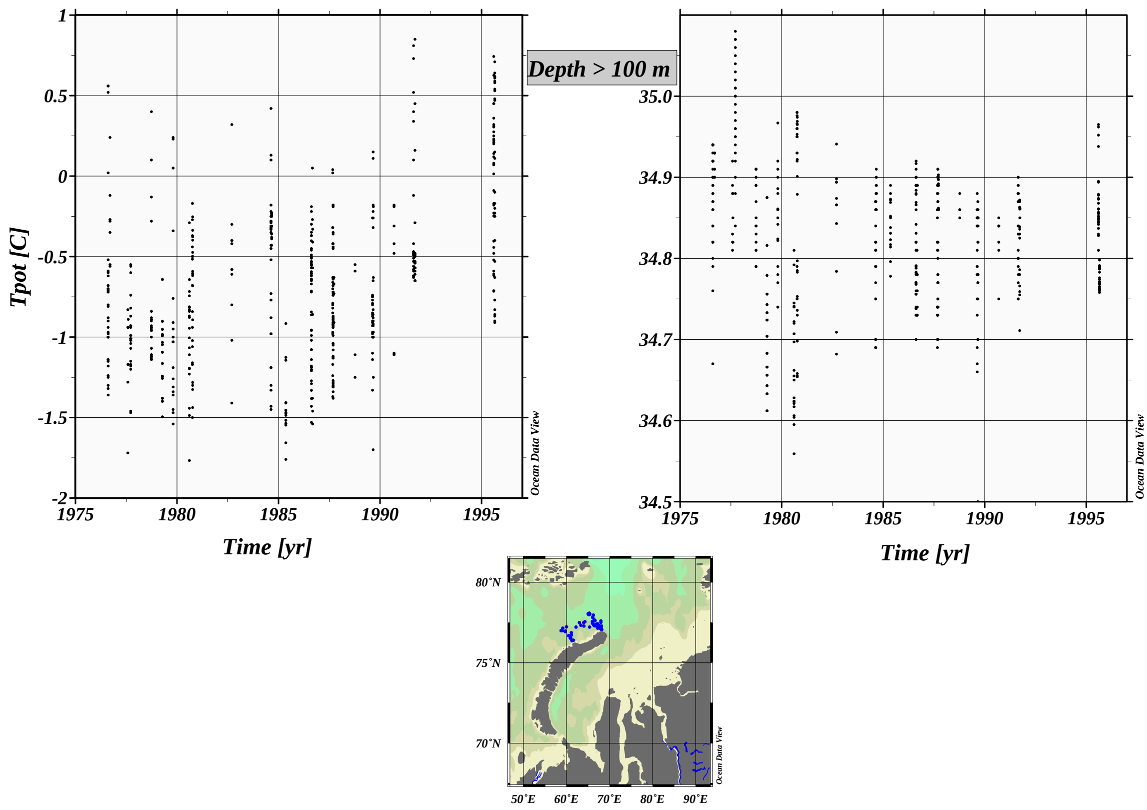


Fig 8: Observed temperature (upper left) and salinity (upper right) against time at the southern part of the passage between Franz Josef Land and Novaya Semlya which captures the eastward flowing water of Atlantic origin below 100 m depth. Also shown are a map with the locations of the observations (lower left).

Horizontal and vertical sections

In the present section we will analyze horizontal maps of the temperature distribution from observations and from the model. We will also analyze vertical sections from Franz Josef Land to the northern tip of Novaya Semlya. The sections were constructed by sampling all data located in a band of 70 km width around the central line. For the horizontal and vertical compilations an interpolation was performed which is based on a weighted-averages scheme using data from the neighborhood of each grid-point. For the construction of meaningful horizontal and vertical sections the amount of available data in the respective year was the limiting factor. We will show data from the years 1984, 1987, 1991 and 1993 since these have sufficient observational data coverage and represent extremes of interannual variability.

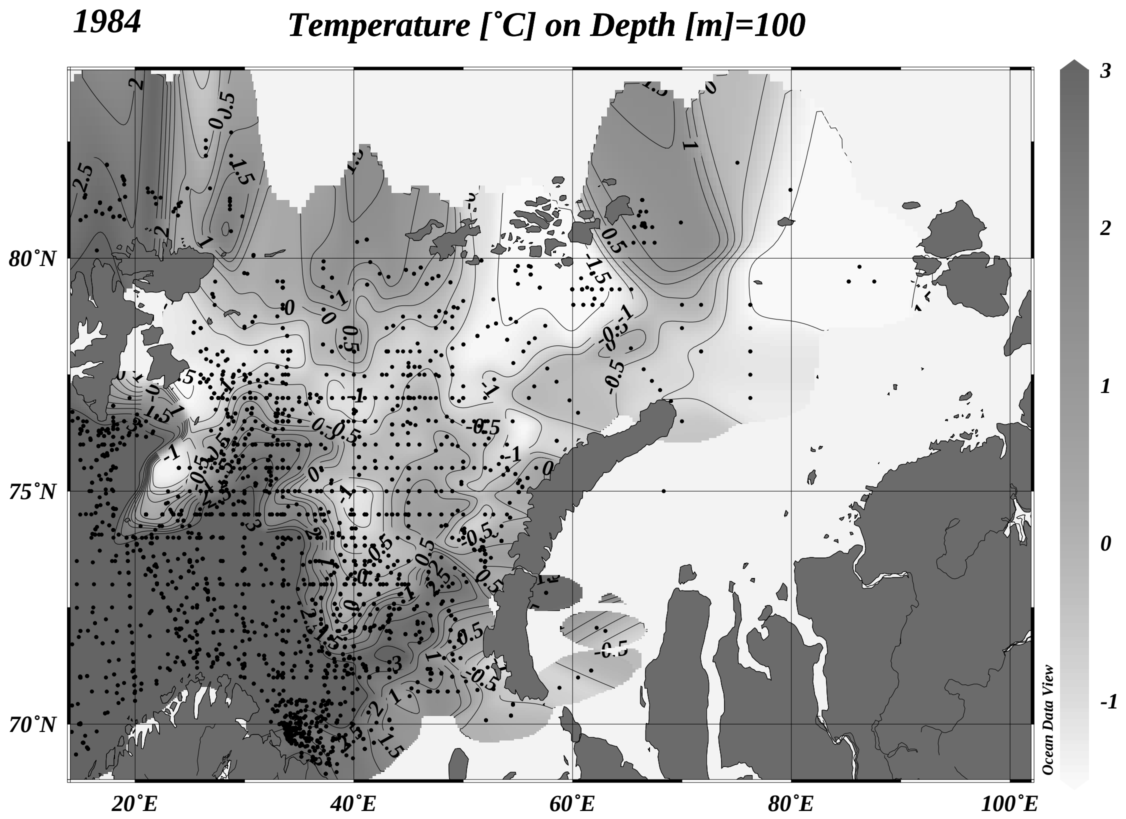


Fig 9a: Observed temperature distributions in summer of 1984 on the 100 m depth level.

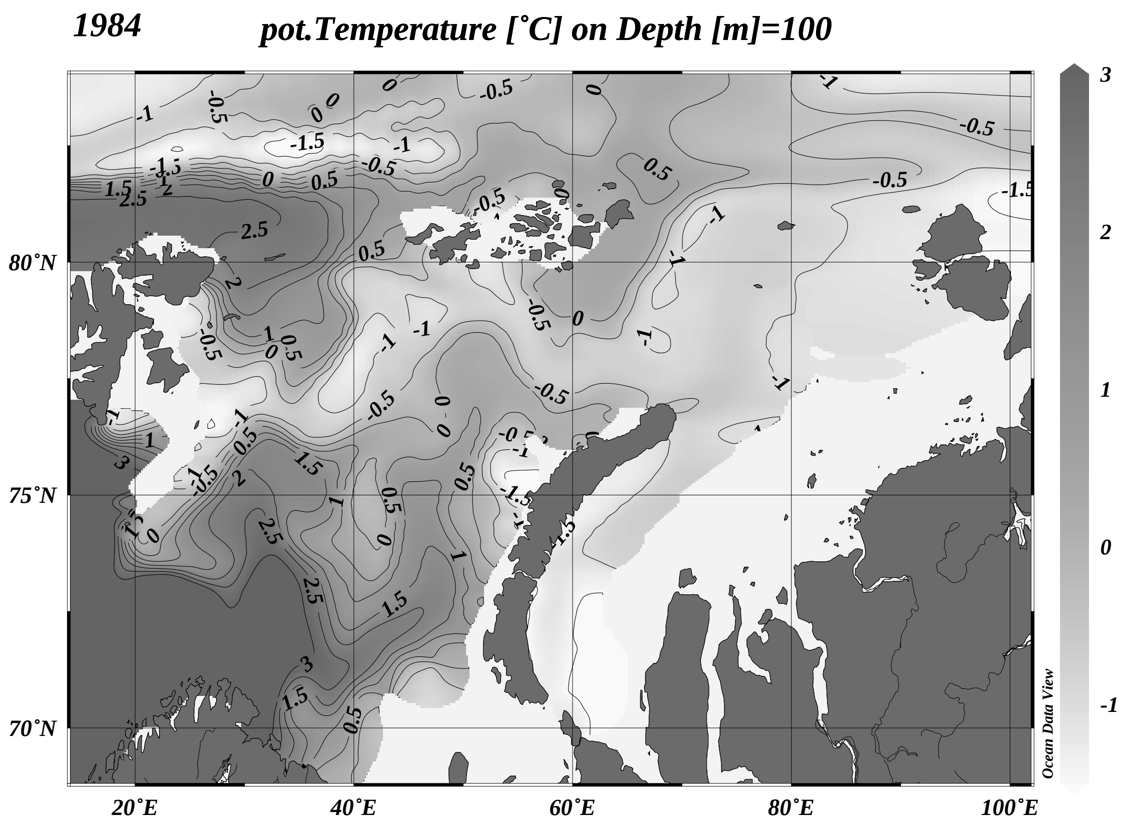


Fig 9b: Modeled temperature distributions in summer of 1984 on the 100 m depth level.

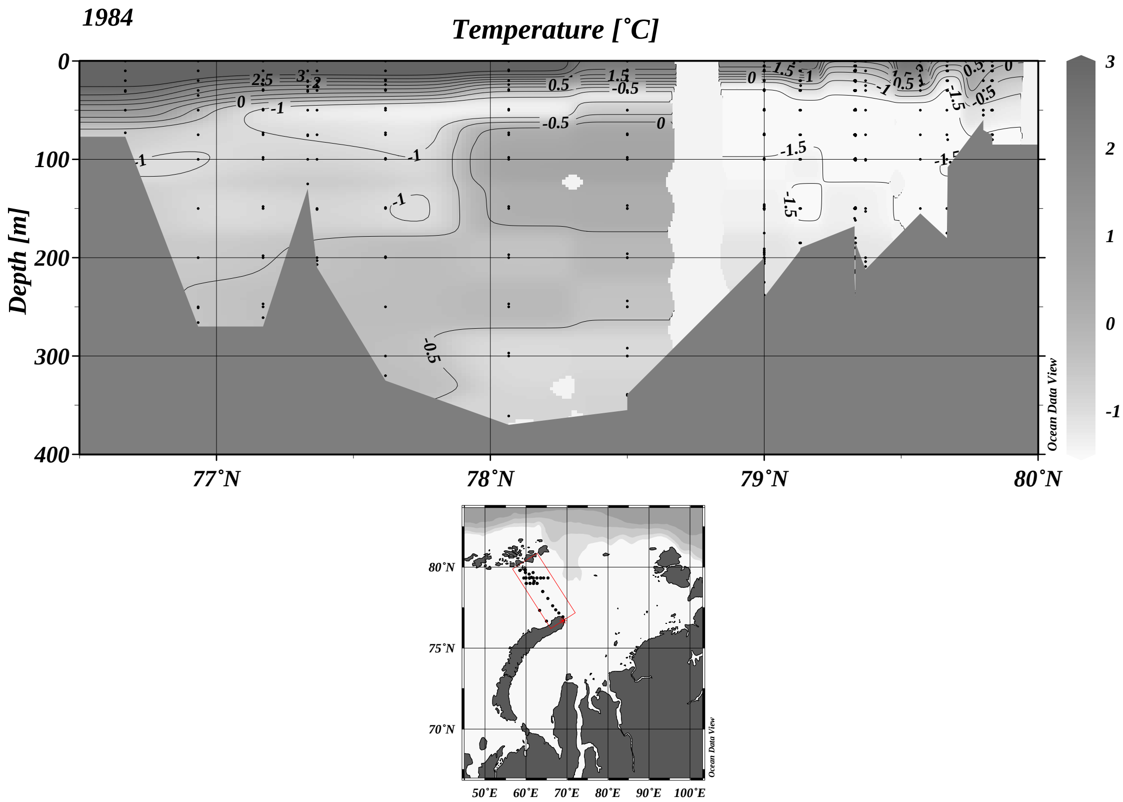


Fig 9c: Observed data for the same time as in Figure 9 a) and b) on a vertical section from Franz-Josef-Land to the northern tip of Novaya Semlya.

The depth level of 100 m is chosen to represent the Atlantic Water flow through the Barents and Kara Seas. The authors are aware of the fact that deep reaching (>100 m) mixed layers as remnants of winter processes may obscure the picture especially with respect to the interpretation of the horizontal maps. On the deeper levels there are less available observations to compared with. The model results shown here represent means of the entire summer halfyear (June to November) while the temporal (and spatial) distribution of the observed data in this period may be very inhomogeneous.

The temperature distribution at 100 m depth in the summer of 1984 from observations (Fig. 9a) and the model simulation (Fig. 9b) are similar and reveal the classical pattern of warm Atlantic Water reaching from the BSO eastward onto the Barents Sea shelf in two tongues. The southern tongue stretches eastward to the Novaya Semlya coast. The central tongue stretches northward with only little eastward expansion. Both model and observations, show temperature minima above the Central Bank and a band of minimum temperature from the southeastern Spitsbergen coast to the area south of Franz Josef Land. Also a warm tongue of the recirculating Fram Strait branch water south of Franz Josef Land is apparent.

In the observed data, however, the warm tongue has a position which is detached from the Franz Josef Land coast further south than in the model. The vertical section at the passage from Novaya Semlya to Franz Josef Land (Fig. 9c) shows this warm water tongue at 80 to 150m depth with maxima between 0.0°C and 0.5°C. The core of the Barents Sea Water which is found on the bottom slope north of Novaya Semlya (approx. 77 - 78°N) exhibits maximum temperatures of -0.5°C to 0.0°C. In 1987 (Fig. 10a, b) the southern tongue of warm Atlantic Water reaching towards Novaya Semlya is significantly colder

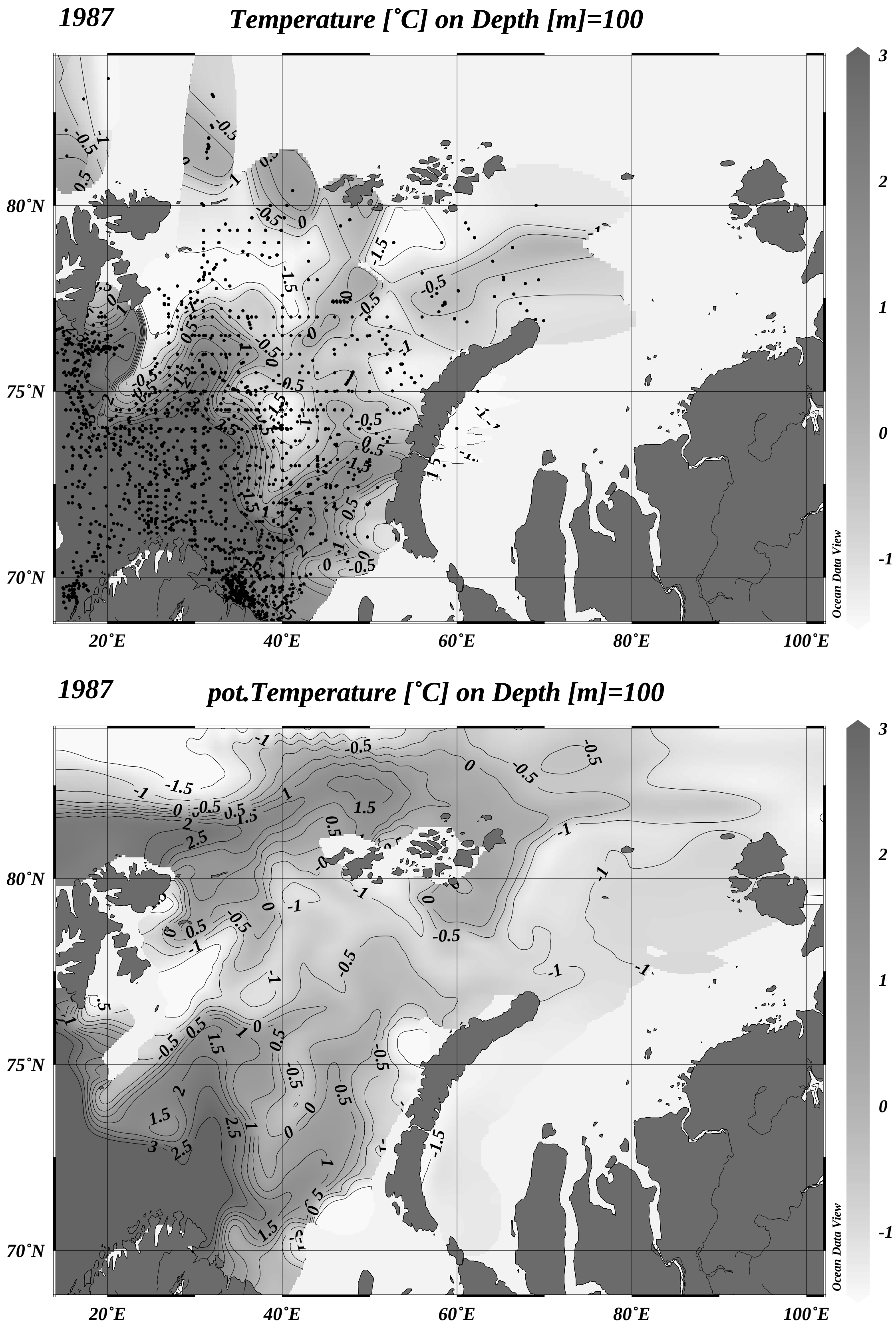


Fig. 10: a) Observed and b) modeled temperature distributions in summer of 1987 on the 100 m depth level on a vertical section from Franz Josef Land to the northern tip of Novaya Semlya.

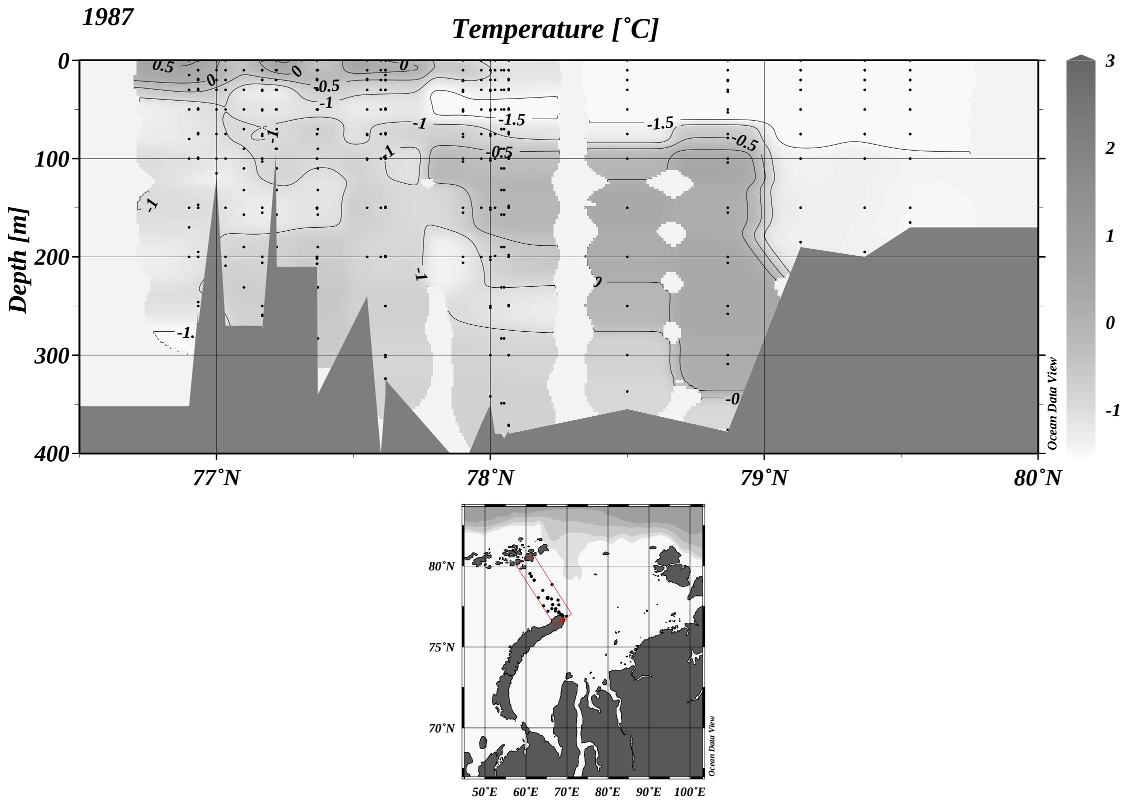


Fig. 10c: Composite of observed data for 1986 and 1987 on a vertical section from Franz Josef Land to the northern tip of Novaya Semlya.

than in 1984: at 50°E by at least 1°C. In comparison to 1984, the central tongue of Atlantic Water in model and observations shows a more prominent eastward extension beyond 40°E pointing towards Franz Josef Land. This may be a hint to differences in circulation pathways with Atlantic Water which is not only colder but moves along a more northern path as compared to 1984.

The colder conditions at the passage between Franz Josef Land and Novaya Semlya are reflected also in a vertical section (Fig. 10c). Here the data from two summers (1986 and 1987) are combined in one composite figure to get a clearer picture of the structure of the otherwise sparse data. This seems justified taking into account the similarity of the temperature range in that area in these two 'cold phase' years. While the temperatures of the Fram Strait branch water entering from the northeast are similar to 1984, the Barents Sea Water is observed with -0.5°C to -1.0°C only. Since for the early 1990s the data coverage of the combined AARI and BarKode data is not sufficient for the construction of a horizontal map, a temperature map derived from Norwegian Fisheries investigations (ANON, 1992) is taken into account (not shown). This chart exhibits temperatures at 100 m depth for September which exceed 0°C as far north as 78°N at 45°E, indicative of a strong central tongue and generally warmer conditions, features which are also found in the model data (Fig. 11a). The temperature increase as compared to 1987 is apparent in both Atlantic Water tongues in the Barents Sea and amounts to approximately 1°C. A vertical section at the passage between Franz Josef Land and Novaya Semlya (Fig. 11b) reflects the warm conditions of the southern tongue showing temperatures above -0.5°C for the Barents Sea Water. Apparently also the recirculating Fram Strait branch is warmer than in the previous years and shows temperatures above 1.5°C. This reflects the warming of the West Spitsbergen Current at Fram Strait after 1989. The warm pulse reached the

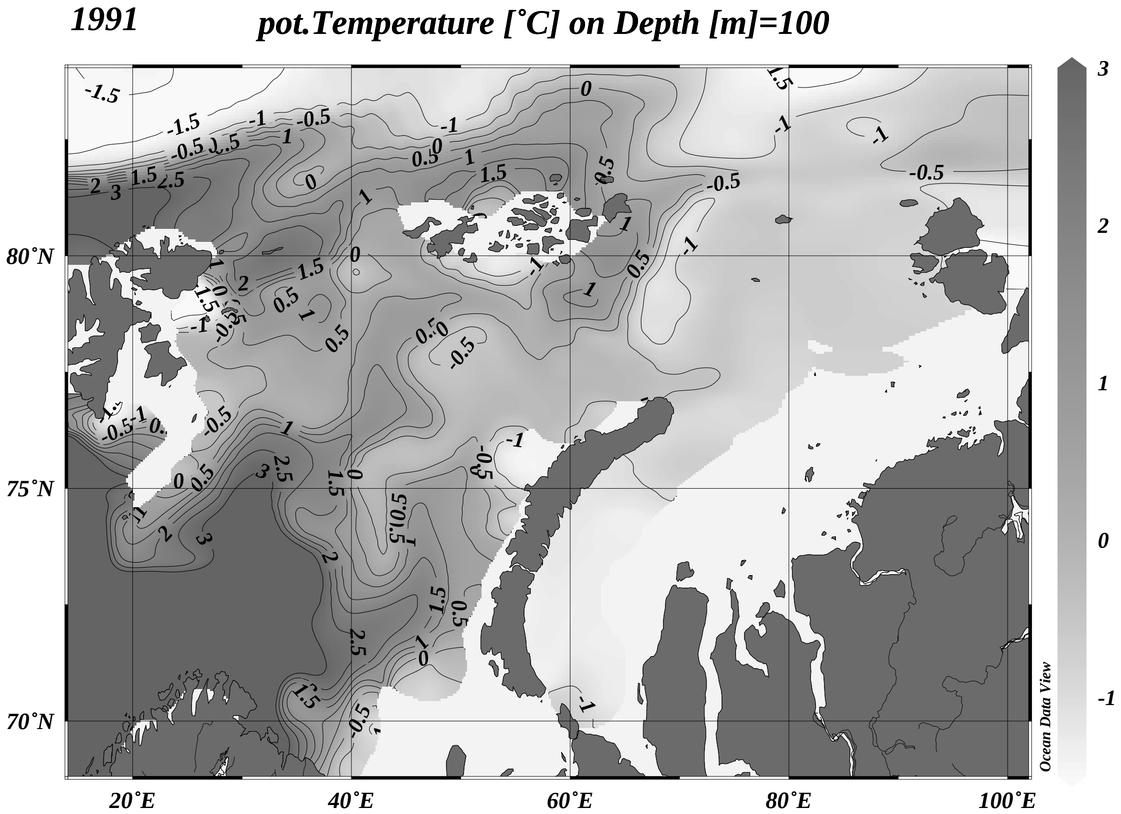


Fig. 11a: Modeled temperature distributions in summer of 1991 on the 100 m depth level.

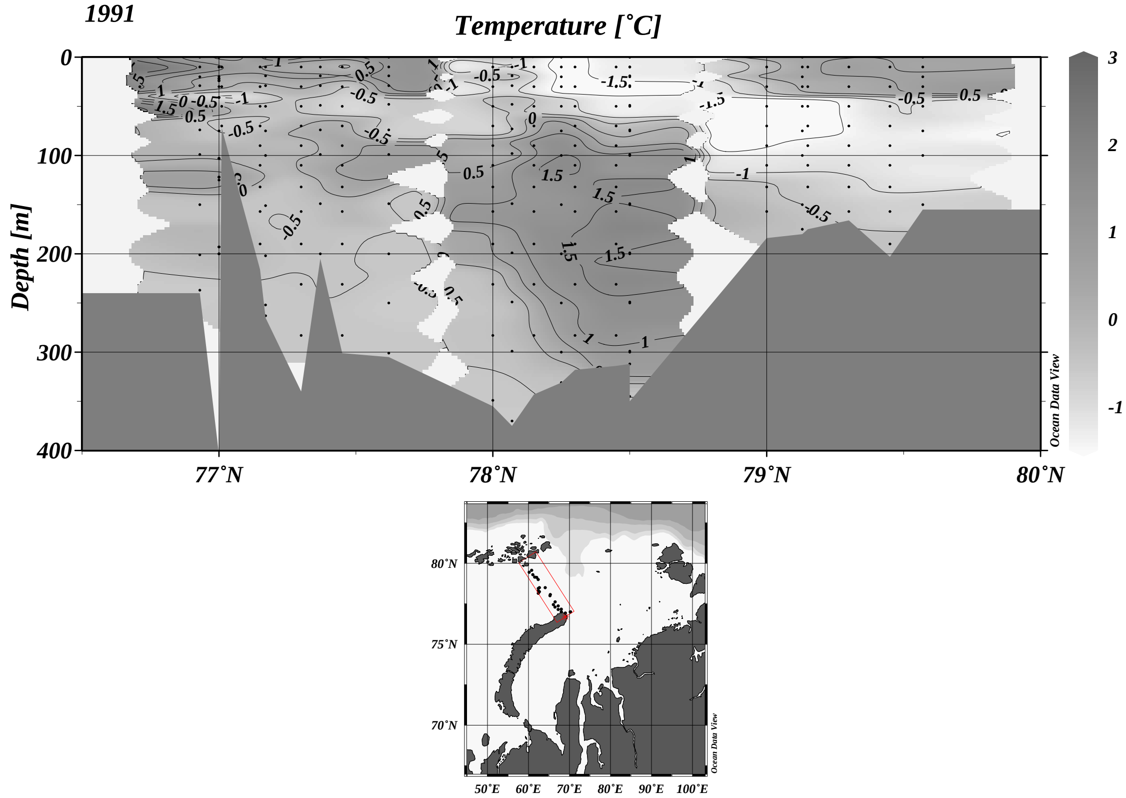
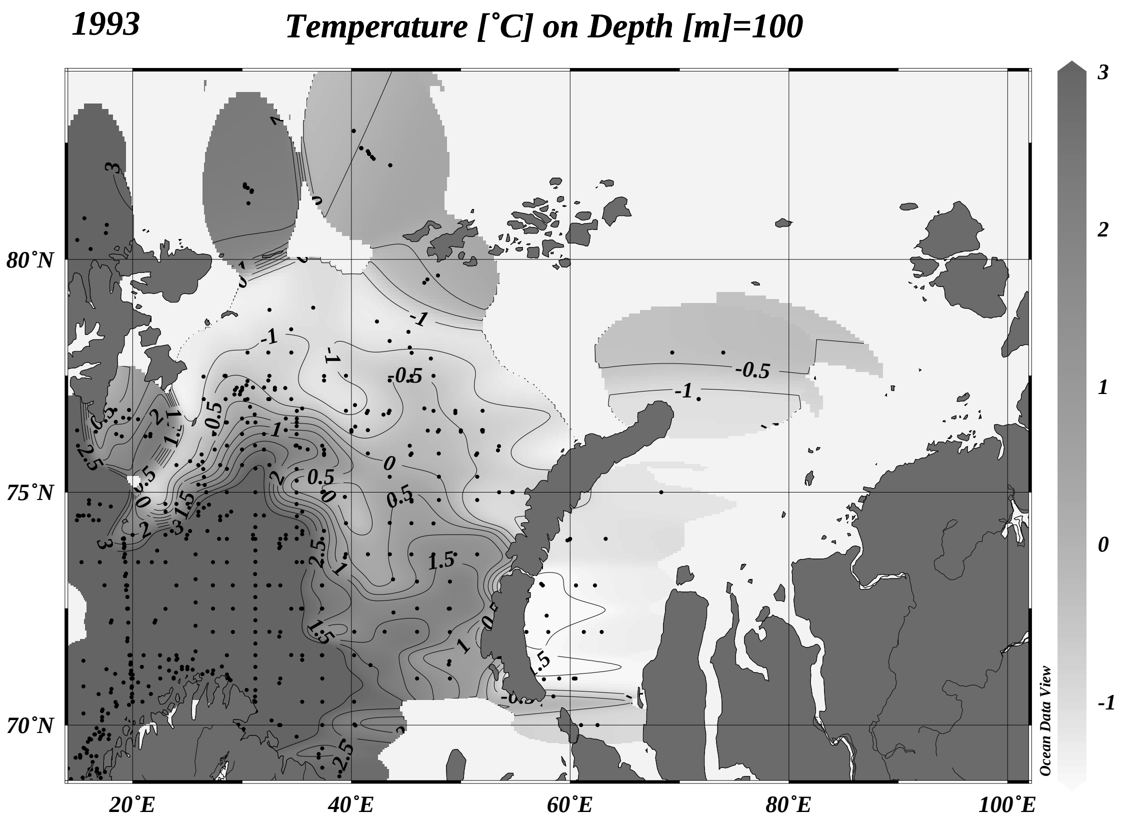


Fig. 11b: Observed data for the same time on a vertical section from Franz Josef Land to the northern tip of Novaya Semlya.



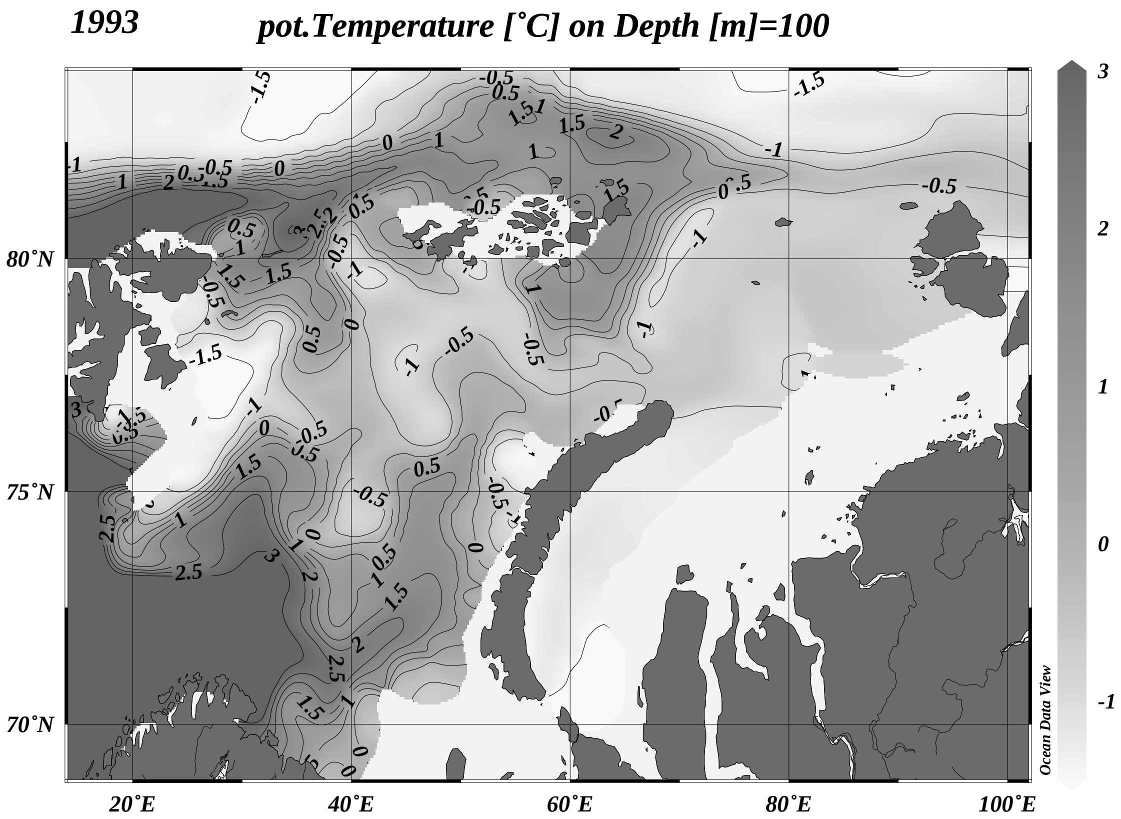


Fig. 12: Observed (a) and modeled (b) temperature distributions in summer of 1993 on the 100 m depth level.

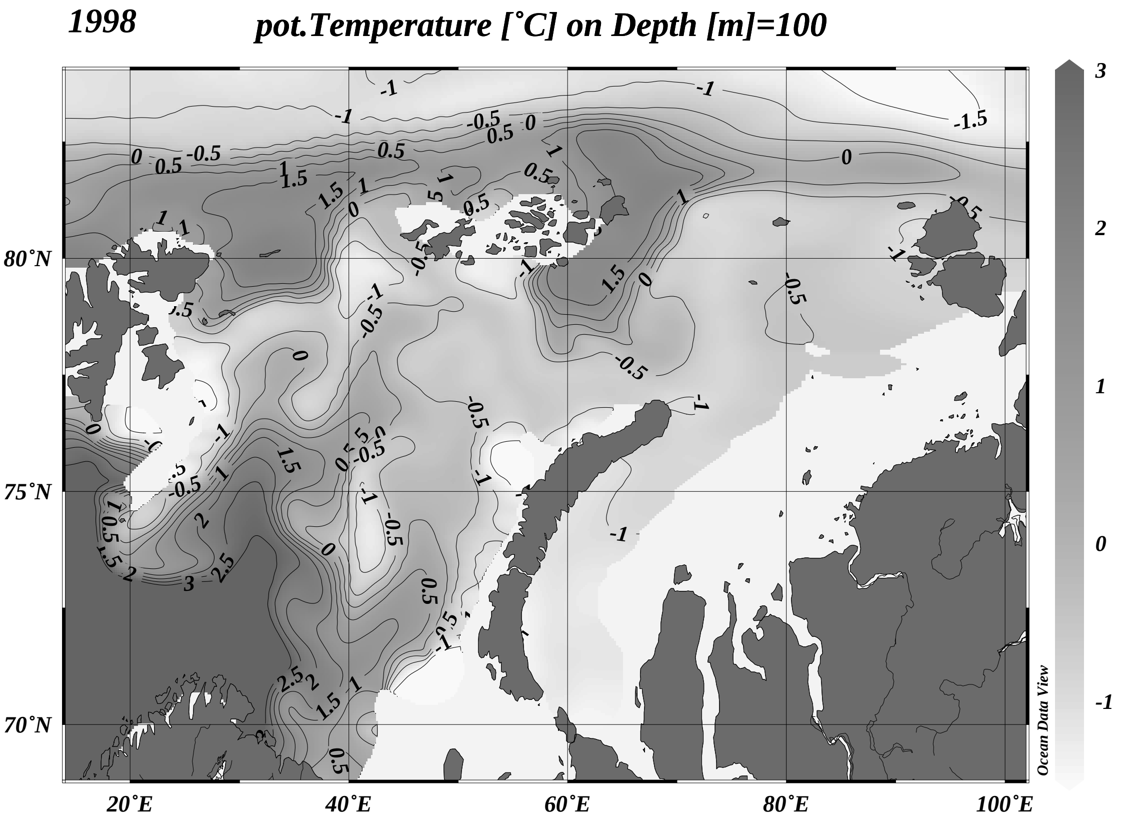


Fig. 13: Modeled temperature distributions in summer of 1998 on the 100 m depth level.

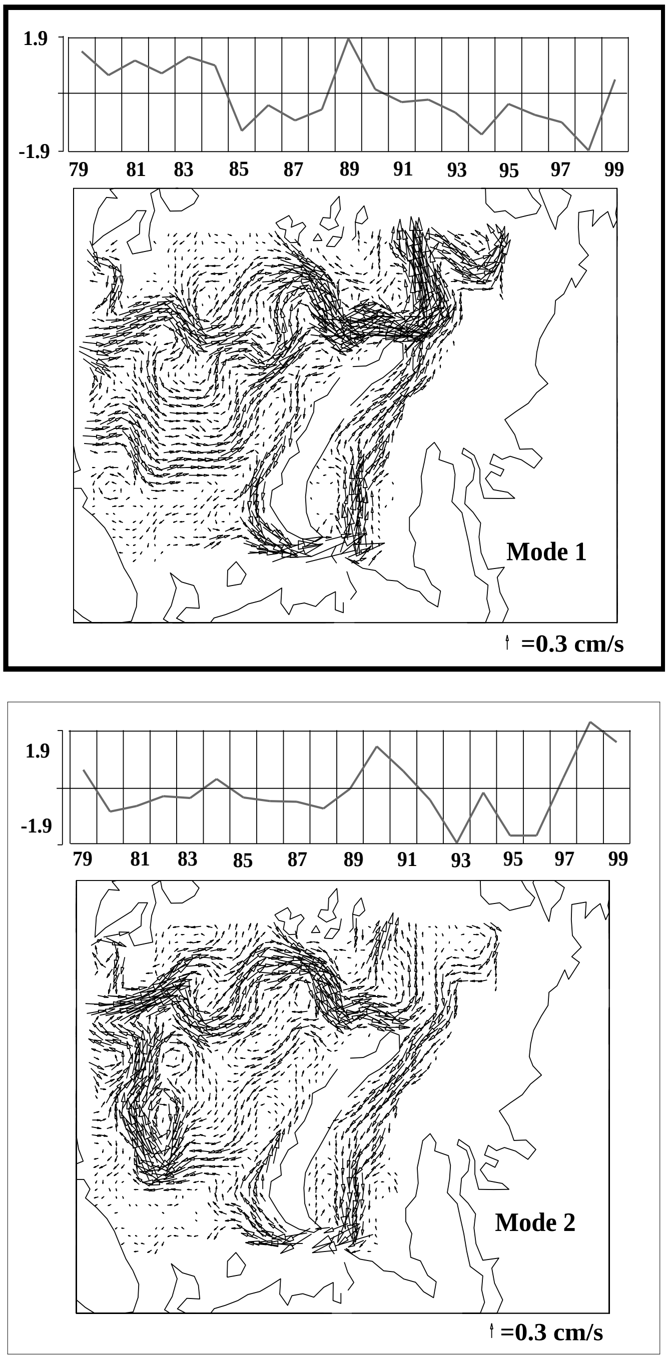
longitude of Franz Josef Land in 1990/91, as was deduced from observations and model results (Quadfasel et al., 1991; Karcher et al., 2003).

While the warm event in the Fram Strait Branch Water continued throughout the first years of the 1990s, also the Barents Sea received increased and anomalously warm inflow of Atlantic Water during several years (Zhang et al., 1998; Karcher et al., 2003).

Observations from 1992 and 1993 (Loeng et al., 1994) indicate both branches of Atlantic Water in the Barents Sea were warm. Model and observations reveal a strong extension of the southern tongue along the west coast of Novaya Semlya, but less pronounced central tongue (Fig. 12a, b). In contrast to 1991 this suggests the warm conditions southwest of Franz Josef Land to be rather a result of Fram Strait Branch Water intruding from the Nansen Basin than of heat carried with the central branch of the Atlantic Water in the Barents Sea.

For the years following 1993 the observational data coverage is not sufficient to draw horizontal maps. We therefore have to rely on the modeled data for a description of the mid to end 1990s. From 1995 to 1998 observed and modeled inflow temperatures at the BSO are anomalously low again (Fig. 2). There is no indication for an advection of this cold anomaly to the passage between Franz Josef Land and Novaya Semlya from the model. This was also evident from the analysis in the previous sections. A reason is the reduced total surface heat loss over the Barents and Kara Sea area in the years 1993-1996, a result of anomalously warm air temperatures (Karcher et al., 2003).

In 1998 we had found a strong drop in temperatures at the two inflow passages (section 3.2). For the Kara Strait 1998 even showed a long lasting westward net flow through the strait. This is reflected in the horizontal temperature field for 1998 (Fig. 13). The southern Atlantic water branch and even more so the coastal water west of Kara Strait, are



a)

b)

Fig. 14: Spatial patterns and timeseries of the first two modes of an EOF (Empirical Orthogonal Function) analysis performed with the yearly mean velocities at 80 m depth from the area filled with vectors. For a proper interpretation of the intensity of the patterns, each velocity vector has to be multiplied with the amplitude of the timeseries at a given year.

unusually cold. The central branch, on the other hand, is characterized by a warm tongue reaching far northeastward.

Horizontal patterns of flow

The comparison of model results and observations performed in the previous sections indicated a pattern of interchanging intensity for the two Atlantic Water branches which cross the Barents Sea. To further investigate this feature we performed an Empirical Orthogonal Function (EOF) analysis of the yearly mean modeled velocity fields for the investigated domain (Fig. 14). The first two modes explain 36 and 27 percent of the variance, respectively. The first mode is associated with a broad intensified flow through the Barents Sea. The central and southern branches are anomalously strong.

The southern branch is detached from the western Novaya Semlya coast, which appears as anomalously southward directed vectors in the modal pattern. This mode is also associated with a strong flow through the Kara Strait and an intense flushing of the entire Kara Sea. The timeseries for this mode reveals that the low Kara Strait throughflow years 1985 to 1987 and 1998 (Fig. 5) were associated with a negative state of this mode. To better understand the atmospheric stress patterns associated with this mode we computed the Sea level Pressure (SLP) patterns associated with the two modes (Fig. 15). For the first mode the associated SLP pattern is characterized by a low pressure anomaly over the Nordic Seas, which is likely to enhance the cyclonic circulation in there. This in turn is in favor of an increased inflow of Atlantic Water into the Barents Sea. Also the SLP pattern over the Barents Sea with a SLP gradient from west to east imposes a local forcing which creates an intensified throughflow through the Barents and Kara Seas.

A positive state of the second mode, on the other hand, is associated with a reduced flow through the Kara Sea and the Kara Strait, as is evident from the tine series in the period 1989 to 1991 and in 1998/99. The second mode has its largest realization in 1998, when the modeled time series for the Kara Strait throughflow (Fig. 5) was strongly reduced, even reversed. This mode also exhibits a decreased velocity of the southern branch of Atlantic Water in the Barents Sea while the central tongue is intensified towards northeast. The fact that the volume flux through the Franz Josef Land to Novaya Semlya passage is enhanced in 1998 and 1999 seems mainly due to the strong state of the second mode in these years. The temporal behavior of this pattern is consistent with the interpretation of the observed and modeled temperature patterns at 100 m depth presented in the previous section: the central tongue is strong in the period 1989 to 1991 and has its maximum value in 1998. The associated SLP for this second mode (Fig. 15) shows a much smaller scale pattern over the investigated area. It exhibits a positive SLP anomaly over the northern tip of Novaya Semlya.

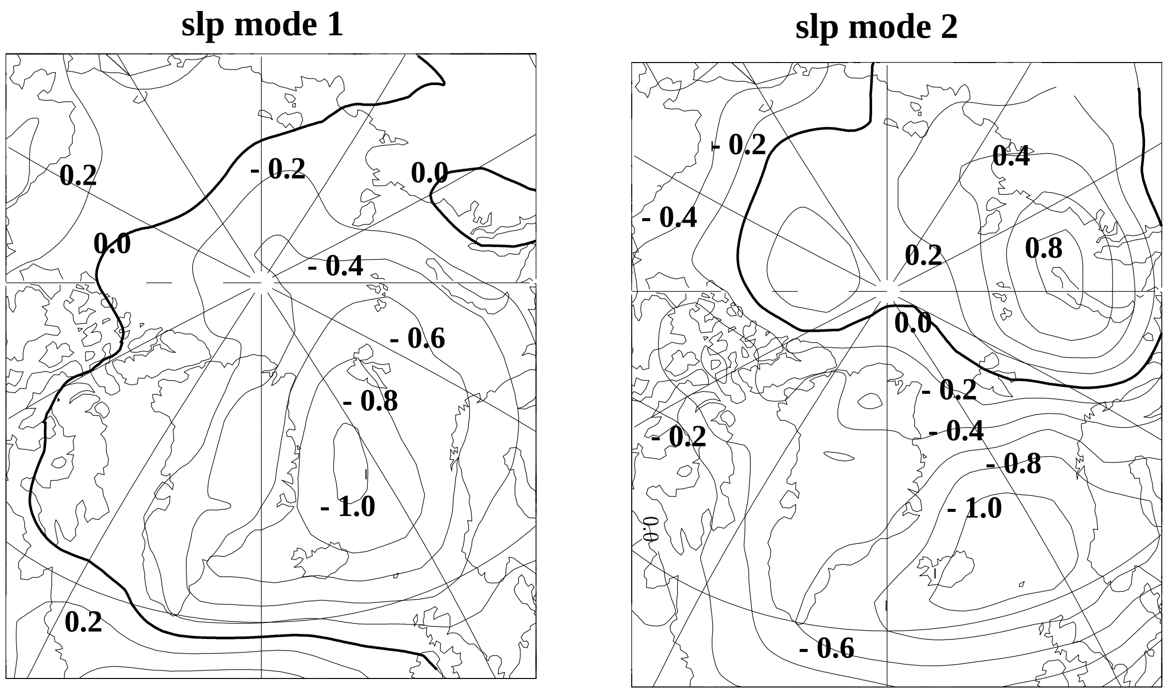


Fig. 15: Sea level pressure associated with the first two modes of the timeseries of velocity-modes shown in Figure 14.

The resulting wind stress pattern is directed against the eastward flow of southern branch in the Barents Sea and the Kara Strait throughflow. In the central and northern part of the Barents Sea the eastward flow profits from the high pressure above Novaya Semlya, as was the case in the year 1998 and 1999. The timeseries of the second mode velocity patterns and the associated SLP pattern for the second mode bear a large similarity to the second mode of modeled and observed winter sea ice concentration in the Barents Sea and the Nordic Seas (Kauker et al., 2003). In their investigation which compares model results and satellite observations with respect to northern hemispheric sea ice, Kauker et al. (2003) find a dipole of ice concentrations and thickness in the eastern Barents Sea for positive states of their second winter mode.

In the years 1998 and 1999 the SLP patterns therefore promoted intensified AW flow on the central branch, which weakens the ice cover there, while in the southern Barents and the Kara Sea the AW flow is weakened and westward movement of ice and water through the Kara Strait is forced.

4 Conclusions

In the present investigation we analyzed model results from 1979 to 1999 and observations of hydrography in the Barents and Kara Seas with respect to the interannual variability of Atlantic Water flow through the western entrances of the Kara Sea. The focus has been on volume and temperature fluxes, as well as on vertical and horizontal sections of temperature distributions. The investigation is a first step to better understand the nature of the interannual variability of Atlantic Water flows on the Barents and Kara Sea shelves. Model results and observations are consistent in their suggestion of the propagation of sequences of warm and cold anomalies through the Barents Sea and subsequently through the Kara Strait and the passage between Franz Josef Land and Novaya Semlya. Most prominent are anomalously cold years 1986, 1993 and 1998 for the Kara Strait throughflow which are associated with weak eastward or even westward flow over periods up to several months. For the passage between Franz Josef Land and Novaya Semlya, the entire period of the 1990s is characterized by warm deep water temperatures. In the early and late1990s also the eastward volume fluxes are at maximum.

We also find interannual variability in the locations and intensity of flow branches of Atlantic water prior in the Barents Sea. Two main branches are identifiable in velocity and temperature distributions: one central branch which separates at 30°E and moves towards the passage on a northward path touching southern Franz Josef Land and one southern branch which continues along the Siberian and subsequently the Novaya Semlya coastline.

It joins the central branch just west of the passage before entering the northern Kara Sea. Intensity and temperature of the two branches are variable on interannual timescales. An EOF analysis of the yearly mean velocity patterns reveals two dominant modes. The first mode is associated with intensified broad eastward flow in the Barents Sea induced by favorable large scale and local SLP patterns. The second mode is associated with an intense central branch, a weak southern branch and weak or reversed flow through Kara Strait, as was the case in the late 1990s. This mode also has a strong link to changes in the ice cover of the Barents and Kara Seas.

In this study we have been able to show that the modeled interannual variability of temperatures of the Atlantic Water entering the Kara Sea are consistent with observations. Additional information, e.g. on the volume fluxes and changes in upstream flow fields, have been gained from the model. However, many open questions remain with respect to the interaction of the Atlantic Water fluxes with local and large-scale ambient conditions: the variability of salinity, the interplay of surface stresses by wind and ice, the interaction of the ice cover variability and the surface heat fluxes and their effect on heat and salt balances for the Barents and Kara Sea will have to be elucidated in forthcoming studies.

Acknowledgments

The authors would like to express their gratitude towards the agencies which funded part of this work: the European Union under EC MAST III program through grant MAS3-CT96-0070 (VEINS), and the German Ministry for Education and Research (BMBF) together with Russian authorities in the framework of the Russian-German project 'Siberian River Runoff (SIRRO)'. The authors also want to thank two reviewers for providing constructive criticism which helped to improve the manuscript. Financial support by the German Ministry of Education, Science, Research and Technology (BMBF) (grant no. 03G0547A) and the Russian Foundation of Basic Research is gratefully ackowledged.

This material is based upon work partially supported by the National Science Foundation under Agreement No. OPP-0002239 with International Arctic Research Center, University of Alaska Fairbanks (Arctic Ocean Model Intercomparison Project). Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

References

ANON, 1992. Datarapport fra Planktonundersokelser i Barentshavet 1991. Institute of Marine Research Bergen, 10/1992/HSMM.

Carmack, E. C., R. W. MacDonald, R. G. Perkin, F. A. McLaughlin, R. J. Pearson, 1995. Evidence for warming of Atlantic Water in the southern Canadian Basin of the Arctic Ocean: Results from the Larson-93 expedition. Geophys. Res. Lett. 22, 1061-1064.

Gibson, J.K., Kallberg, P., Uppala, S., Nomura, A., Serrano, E., Hernandez, A., 1997. ERA description. ECMWF reanalysis project report 1: Project organization, European Centre for Medium Range Weather Forecast, Reading, UK.

Golubev, V.A., A. N. Zuyev, Barents and Kara Seas Oceanographic Data Base (BarKode), 1999. Edited by: C. Oelke, International ACSYS/CLIC Project Office, Murmansk/Tromsø, Russia/Norway.

Gorshkov, S. G., Atlas of Oceans, 1980. Arctic Ocean. Military Defence Publishing House, Moscow.

Harder, M., P. Lemke, M. Hilmer, 1998. Simulation of sea ice transport through Fram Strait: Natural variability and sensitivity to forcing. J. Geophys. Res. 103, 5595-5606.

Harms, I.H., M. J. Karcher, 1999. Modelling the seasonal variability of hydrography and circulation in the Kara Sea J. Geophys. Res. 104, 13431-13448.

Hibler, W.D., 1979. A dynamic thermodynamic sea ice model. J. Phys. Oceanogr. 9, 815-846.

Hibler, W.D. III, Bryan, K., 1987. A diagnostic ice-ocean model, J. Phys. Oceanogr. 17, 987-1015.

Karcher, M.J., R. Gerdes, F. Kauker, C.Köberle, 2003. Arctic warming - Evolution and Spreading of the 1990s warm event in the Nordic Seas and the Arctic Ocean, J. Geophys. Res., in press.

Kauker, F., R. Gerdes, M. Karcher, C. Köberle, J. Lieser, 2003. Variability of Northern Hemisphere sea ice: A combined analysis of model results and observations from 1978 to 2001. J. Geophys. Res., in press.

Köberle, C, R. Gerdes, 2003. Causes of Arctic sea ice volume variability, J. Clim., submitted.

Levitus, S. and Burgett, R. and Boyer, T., World Ocean Atlas 1994, vol. 3, Salinity, and vol. 4, Temperature, NOAA Atlas NESDIS 3 & 4, U.S. Dep. of Comm., Washington D.C., 1994.

Loeng, H., R. Saetre, 2001. Features of the Barents Sea Circulation, Fisken og Havet 1.

Loeng, H., L. Midtun, H. Sagen, 1994. Current measurements between the central and great banks in the Barents Sea. Fisken og Havet 3.

Loeng, H., L. Ozhigin, V., B. Adlandsvik, 1997. Water fluxes through the Barents Sea, ICES J. Mar. Sci. 54, 310-317.

NSIDC, 1997. Environmental Working Group, Joint U.S. Russian Atlas of the Arctic Ocean, Oceanography Atlas for the Winter Period, CD-Rom, NSIDC/CIRES, University of Colorado, Boulder.

Pacanowski, R.C., 1995. MOM 2 Documentation, user's guide and reference manual, GFDL Ocean Group Tech. Rep. No.3, Geophysical Fluid Dynamics Laboratory, Princeton University, Princeton, NJ.

Pavlov, V., Pfirman, S., 1995. Hydrographic structure and variability of the Kara Sea: Implications for pollutant distribution. Deep Sea Res. II 42, 1369-1390.

Quadfasel, D., A. Sy, D. Wells, A. Tunik, 1991. Warming in the Arctic. Nature 350, 385.

Rigor, I. G., R.L. Colony, M. Seelye, 2000. Variations in surface air temperature observations in the Arctic, 1979—97. J. Clim.13, 896 - 914.

Röske, F., 2001. An atlas of surface fluxes based on the ECMWF Re-Analysis- a climatological dataset to force global ocean general circulation model. MPI-Report 323, Max-Planck-Institut f. Meteorologie, Hamburg, Germany.

Rothrock, D.A., Y. Yu, G.A. Maykut, 1999. Thinning of Arctic sea-ice cover. Geophys. Res. Lett. 26, 3469-3472.

Schauer, U., B. Rudels, E. P. Jones, L. G. Anderson, R. D. Muench, G. Björk, J. H. Swift, V. Ivanov, A.-M. Larsson, 2002. Confluence and redistribution of Atlantic water in the Nansen, Amundsen and Makarov basins. Annales Geophysicae 20 (2), 257-273.

Schauer U, Loeng H, Rudels B, Ozhigin VK, Dieck W, 2003. Atlantic Water flow through the Barents and Kara seas. Deep-Sea Res. I, in press.

Semtner, B., 1976. A model for the thermodynamic growth of sea ice in numerical investigations of climate. J. Phys. Oceanogr. 6, 379-389.

Steele, M. W. Ermold, G. Holloway, S. Häkkinen, D. Holland, M. Karcher, F. Kauker, W. Maslowski, N. Steiner, J. Zhang, 2001. Adrift in the Beaufort Gyre: A Model Intercomparison. Geophys. Res. Lett. 28, 2935-2838.

Zhang, J., D., A. Rothrock M. Steele, 1998. Warming of the Arctic Ocean by a strengthened Atlantic inflow: Model results. Geophys. Res. Lett. 25, 1745-1748.